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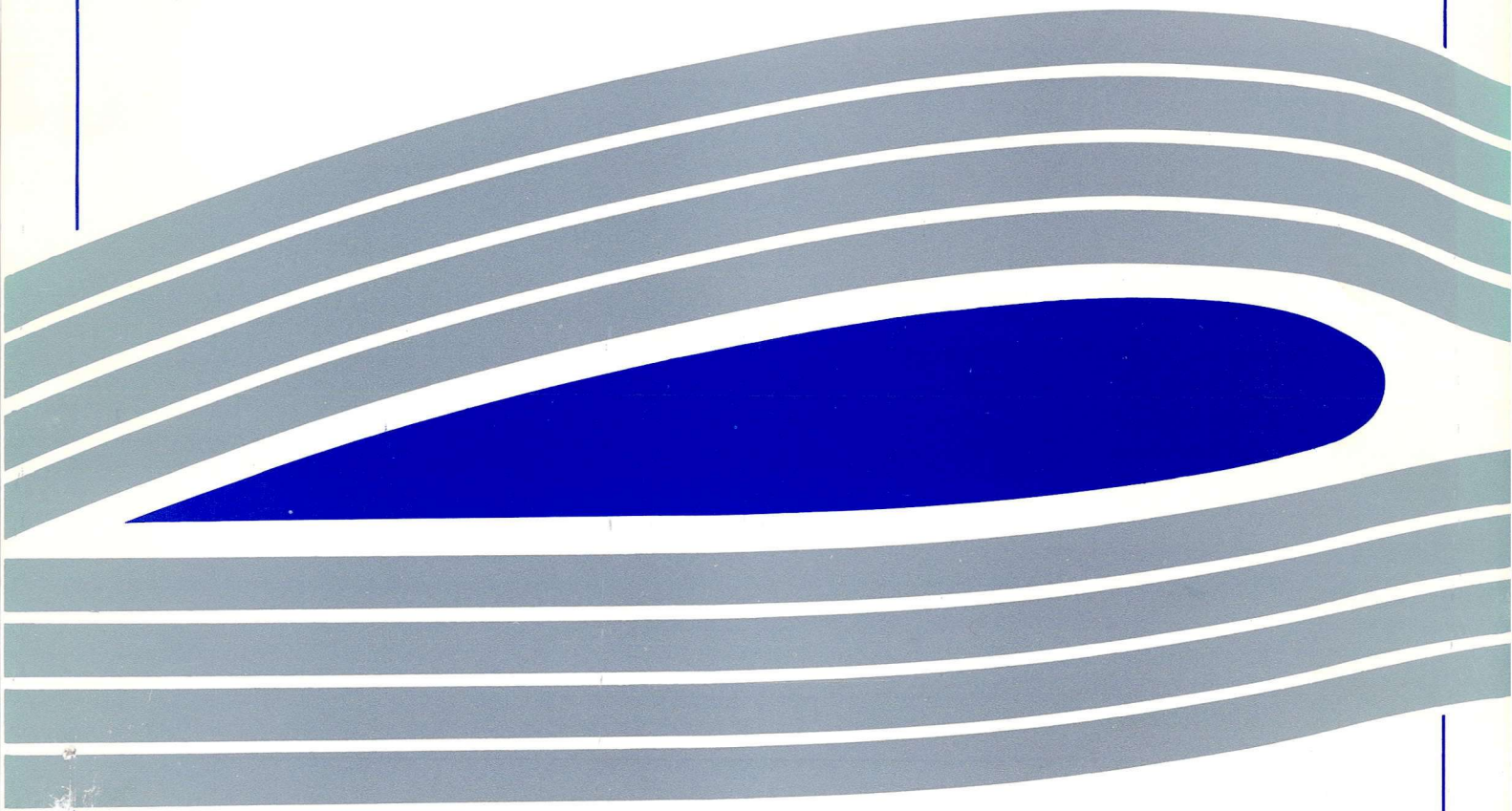


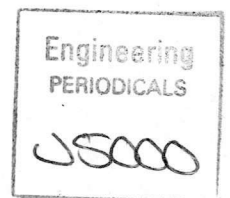
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**AN INVESTIGATION OF RE-
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STALL IN UNSTEADY CONDITIONS**

G.U. Aero Report 9431





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SERC/EPSRC final contract report, contract number GR/H16711

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ABSTRACT

The following report summarises a three year research programme in the Department of Aerospace Engineering, University of Glasgow to investigate re-attachment over two-dimensional aerofoils performing pitching motion. The original motivation for the work was to understand how an aerofoil could generate negative lift coefficients at large positive angles of incidence (e.g. 10°) during so-called ramp-down motions from high to low incidence. An extensive database of unsteady pressure measurements on thirteen aerofoils provided the basis for the analysis. This was supplemented by a number of specific tests, including an examination of the wind tunnel constraint effect using a high aspect ratio model. Additionally, a smoke flow visualisation facility was developed and used to examine particular aspects of the phenomenon identified in the pressure analysis. To complement the analytical work, a discrete vortex method and a semi-empirical dynamic stall model were applied to the ramp-down problem. The work resulted in a definitive physical description of the dominant mechanisms present in the ramp-down process. The work also validated the use of a universal time-delay within the Beddoes semi-empirical dynamic stall model to represent the variation of aerodynamic coefficients during ramp-down.

OBJECTIVES

The specified objectives of the work were to develop a physical description of the re-establishment of fully attached flow under unsteady conditions and to apply this knowledge to the development of a semi-empirical model for reconstruction/prediction of aerodynamic coefficients during ramp-down.

METHODOLOGY

It was intended to make extensive use of an existing database of pressure measurements and to supplement this with a limited number of additional tests. A smoke flow visualisation facility was to be developed and used to study specific aspects of the ramp-down process highlighted during the pressure analysis. A semi-empirical dynamic stall model and a discrete vortex method were to be applied to the ramp-down problem as the analysis progressed.

OVERVIEW OF EXPERIMENTAL PROGRAMME

Pressure data sampling

A considerable amount of pressure data were already at the Department's disposal, and only a small amount of additional testing was deemed necessary. Tests were, however, carried out on a high aspect ratio NACA 0015 model to assess wind tunnel constraint effects. Additionally, a series of ramp-down tests was conducted on models with a leading edge sand strip.

Smoke flow visualisation

This phase of the research initially involved establishing a flow visualisation wind tunnel and then setting up an unsteady aerodynamics facility within it. It was also necessary to develop appropriate photographic techniques prior to testing a NACA 0015 model.

Aerofoil pitching motion may be generated without the need for feedback control by use of a stepper motor. The stepper motor was programmed using LABVIEW running on a Macintosh LCIII computer with a

data acquisition board installed. A particular benefit of the stepper motor system is its ease of modification for other applications; all that need be considered is the transfer function between the stepper motor motion and the model motion. Thus the system proved to be simple to use and highly effective. Further details are described by Green (1994).

For unsteady flow visualisation, cine photography is fast but cumbersome, while still photography needs numerous runs to record a single sequence of events. Video recording and frame grabbing offer the possibility of cine photography at up to twenty five frames per second with adequate resolution (see, for example, Fig. 1.), and thus the lengthy processing needed for conventional photography is eliminated. Hardware compression technology and affordable high speed desktop computers have made the video option very attractive, and so a Macintosh based system was acquired at the University's expense. This has proved to be a very powerful analysis and presentation tool.

PRESSURE DATA ANALYSIS

This work constituted the main effort of the research. It consisted of a comparison of pressure data from two NACA 0015 models to assess tunnel constraint effects, and an in-depth analysis of the pressure data from other aerofoils to determine a physical description of the flow behaviour during ramp-down motion.

Consideration of wind tunnel effects

The analysis of constraint effects was essentially a continuation of the work of Niven & Galbraith (1990). They concluded that the flow behaviour could not be explained by induced incidence effects within the wind tunnel environment.

In the present work, a comparison of data from the two NACA 0015 models (one with half the chord and twice the aspect ratio of the other) showed that the gross features of the ramp-down flow behaviour were the same for both models, i.e. they produced the phenomenon of negative lift at large positive incidence, and the shape of the normal force against incidence curves were the same. Closer examination revealed small differences in the chordwise attachment history and the characteristic ramp-down time delay. Thus it was concluded with some confidence that the salient observations from the ramp-down data were those of a two-dimensional flow, although the quantitative values were affected by wind tunnel interference. A broader description is given by Green & Galbraith (1992, 1994b).

Effect of leading edge roughness

A limited series of tests were conducted on models with a leading edge sand strip to assess the sensitivity of the observed phenomena to the mechanism of transition. In the ramp-down case, the addition of the roughness element had little influence on the load coefficient behaviour. This result is consistent with the following analysis and highlights the significance of the aerofoil wake during the ramp-down process.

Although not a designated part of the current project work, it was opportune to conduct a number of ramp-up tests on the models with leading edge sand strips. This series of tests showed that, at the test Reynolds number, the application of leading edge roughness significantly altered the detail of the dynamic stalling process. A consideration of these data can be found in Green & Galbraith (1994a).

In-depth analysis of pressure data for ramp-down cases

Figure 2 shows the effect of reduced pitch rate on the $C_N \sim \alpha$ data from a NACA 0015 aerofoil during ramp-down tests from 40° to -1° . As incidence decreases, the normal force falls at an almost uniform rate that is independent of the reduced pitch rate. At sufficiently low incidence the normal force reaches the minimum value, $C_{N \min}$, and then increases. To explain the above behaviour the analysis reported by Niven et al. (1989) and Niven & Galbraith (1990) concentrated upon details of the attachment history. This analysis was repeated as part of the current research. In addition the attachment history over the aerofoil models with the leading edge sand-strip was determined. However, it was found that a consideration of the delay in attachment alone during a ramp-down test could not account for the detailed normal force behaviour. In particular, one model, the NACA 23012C, did not generate negative lift at large positive incidence, even though its attachment history was virtually identical to the other models tested.

An important result reported by Niven et al. (1989) was that the incidence of attachment at the leading edge during a ramp-down test was only a weak function of the reduced pitch rate and was close to the static value. Furthermore, they observed that, from analysis of data from one model, the time between leading edge attachment and the minimum normal force, $C_{N \min}$ (indicated on Fig. 2) was equivalent to

three chord lengths of travel. This analysis was repeated for a number of models during the current research, and it was found that the time delay between the *first observation* of leading edge attachment (this part of the definition is crucial) and $C_{N\min}$ was independent of reduced pitch rate and model shape. Meanwhile the attachment history was observed to be strongly dependent upon the reduced pitch rate, with the result that there is no correlation between when $C_{N\min}$ occurs and attachment position along the aerofoil chord.

The time delay between leading edge attachment and $C_{N\min}$ brought the behaviour of the NACA 23012C model into line with the other models tested. The reason why this model does not generate negative lift at large positive incidence is that leading edge attachment first occurs at a much higher incidence than on any of the other models (about 23° compared to 18°). Hence a sufficiently low incidence is not reached before the end of the time delay. Faster ramp rates, however, could achieve zero lift at positive incidence.

An important corollary of the above analysis is that the negative lift itself is not particularly important. What is important is the extension of the high incidence behaviour to low incidence for the duration of the time delay; negative lift at positive incidence is simply a consequence of this behaviour. The research up to this stage has been reported by Green & Galbraith (1994c).

Further analysis concentrated upon the fluid mechanics behind the time delay. Figure 3 shows a contour plot of the time rate of change of surface pressure on the NACA 23012B. As incidence decreases the suction in the separated flow falls at a nominally uniform rate (note that the suction within the separated flow is uniform). The first significant event is the establishment of attached flow in the leading edge region (beginning at 2.5% chord for this aerofoil). Further attachment progress is represented by the light grey area which lags behind the most dominant feature of the plot highlighted in darker grey. That dominant feature is a wave in which the rate of decrease in suction increases by as much as five times. This disturbance, which travels along almost the entire length of the chord, is observed on every ramp-down test and will be referred to as the ramp-down pressure wave. It was found that $C_{N\min}$ occurred as this wave passed over the trailing edge. The speed of travel of the wave is easily determined, and it is found to be independent of both model shape and reduced pitch rate. Its average speed is approximately half the free stream speed, and, since $C_{N\min}$ occurs as the wave passes over the trailing edge, the travel of the wave accounts for the last two-thirds of the ramp-down time delay.

The observation of the above wave in the ramp-down data and its measurement represent the culmination of the pressure data analysis. This aspect of the flow behaviour has been written up for publication, and has been submitted to the A.I.A.A. Journal. A condensed form of the above work was presented at the 2nd International Conference on Experimental Fluid Mechanics, Torino, Italy (Green et al. (1994)).

FLOW VISUALISATION RESULTS

The low operating speed of the flow visualisation wind tunnel limits the test Reynolds number to about 1×10^4 . This compares unfavourably with the pressure data Reynolds number of 1.5×10^6 . Such a disparity would normally render even qualitative assessment of separation characteristics invalid. For the present tests, however, the initial fully stalled condition is insensitive to Reynolds number. The fundamental phenomena associated with the ramp-down motion should, therefore, be present and observable, albeit the re-attachment of the boundary layer will be different.

Preliminary observations did not provide a substantive explanation of the pressure data behaviour. The delay in attachment to lower incidence was observed, although this was already known to be a secondary effect. Closer examination, however, showed that there was a much greater amount of fluid in the near wake during a ramp-down test than during a static test, i.e. convection of wake fluid from the model was delayed. Figure 1 shows a picture from a ramp-down test. The figure shows that the separation point is very close to the leading edge; a static test at this Reynolds number and incidence shows the separation point further back. In addition the dashed white line roughly represents the wake boundary in a static test; there is clearly a great deal of wake fluid above this line. Another indicator of the presence of excessive wake fluid is the inclination of the smoke lines above the aerofoil surface. The smoke lines slope upwards from right to left, which indicates an obstruction to the free stream flow. Thus the smoke flow visualisation showed that, in addition to shear layer attachment delay, convection of wake fluid away from the aerofoil surface is an important phenomenon in ramp down motion. Results of the smoke flow visualisation have been published by Green & Galbraith (1994b,c) and Green et al. (1994).

APPLICATION OF THE RESULTS TO THE BEDDOES MODEL

Niven et al. (1989) demonstrated good modelling fidelity by the Beddoes model for the NACA 23012B data, by including an appropriate time delay between leading edge attachment and $C_{N \min}$. Thus the present analysis has extended the usefulness of the Beddoes model by stating that the ramp-down time delay is the same for all models and that it starts from the moment the aerofoil incidence falls below the static leading edge attachment incidence. Accurate assessment of the incidence of first leading edge attachment is vital; with the exception of the NACA 23012C, all the models analysed showed the first evidence of movement of attachment close to the 2.5% chord location. The corresponding position for the NACA 23012C model is at about 0.25% chord.

DISCRETE VORTEX MODELLING

A discrete vortex model for the prediction of unsteady flows was developed. This model was applied to ramp-up and ramp-down cases. The results were then animated and the flow behaviour compared to that observed during experiments. A detailed description of this work can be gleaned from Lin & Vezza (1994).

PHYSICAL DESCRIPTION OF THE FLOW DURING A RAMP-DOWN TEST

An important observation is that the ramp-down pressure wave first appears some time after the first observation of leading edge attachment. During this period, attachment does not move very far; for the NACA 23012C attachment is at about 2.5% chord, while, for the remainder of the models analysed, attachment is at about 7% chord. The ramp-down pressure wave travels along the chord faster than attachment. Figure 4 shows the chordwise pressure distributions over the lee surface of the NACA 23012B after the initial formation of the ramp-down pressure wave (at 14°), and 2° later. Note the small suction peak that has grown following leading edge attachment. The ramp-down pressure wave causes the formation of a minimum in the chordwise pressure distribution with an increase in suction towards the trailing edge.

The pressure within the wake is largely governed by the fluid velocity at the wake boundary. Hence, such a pressure gradient within the wake indicates fluid acceleration over the wake boundary, which itself suggests that the wake boundary is curved. Figure 5 shows a possible schematic of the appearance of the wake during a ramp-down test, which is partly based on the observations from the flow visualisation tests. The ramp-down pressure wave may be a manifestation of the partial stagnation of the flow ahead of the mass of excess wake fluid, and the wave travels along the chord as this excess fluid convects over the aerofoil surface. The pressure gradient along the wake assists in convecting the wake fluid by quite literally pushing it away. *

A description of the flow during a ramp-down test thus follows. As the aerofoil pitches down, wake fluid above the aerofoil surface is exposed to the free stream and convected away by it. At some incidence, the flow reattaches over the leading edge. However, a result of the small amount of attached flow over the leading edge is that the fluid now follows more closely the actual surface contour. This fluid then encounters the enlarged wake and must flow around it. The wake fluid responds by experiencing an additional acceleration off the model surface, leaving a thinner wake behind. This reduced wake recedes more gradually as flow attachment progresses along the aerofoil behind the ramp-down pressure wave.

CONCLUSIONS

The salient feature of the flow during a ramp-down test is a dynamic extension of the bluff body flow behaviour to low incidence, with the result that negative lift may be generated at large positive incidence. The phenomena observed have been shown to be the result of predominantly two-dimensional flow development, and wind tunnel constraint only affected the quantitative description of the phenomena. The rate of attachment of the separated shear layer over an aerofoil performing ramp-down motion is strongly dependent upon the aerofoil pitch rate, although the shape of the attachment locus does not show any model dependency. A consideration of attachment alone does not explain the extension of the bluff body like behaviour to low incidence.

The time elapsed between the first observation of establishment of attached flow in the leading edge region and the minimum normal force coefficient (i.e. the end of the bluff body like flow behaviour) is independent of pitch rate and aerofoil shape, and is equivalent to three chord lengths of travel.

* See addendum on last page

A pressure disturbance, the ramp-down pressure wave, was observed to travel along the chord from just behind the leading edge to the trailing edge during ramp-down motion. This disturbance is manifested on the pressure data in the form of an increase in the rate of decrease of suction. The end of the bluff body behaviour (i.e. $C_{N\min}$) was observed to occur when this wave reached the trailing edge. The wave results in a pressure gradient along the wake, with higher suction towards the trailing edge.

The wave appeared approximately one chord length of travel after the establishment of attached flow in the leading edge region, and travelled along the chord at a constant rate. In addition the speed of travel of the wave was independent of pitch rate and model shape, and had a value of half the free stream speed.

Low Reynolds number flow visualisation showed that, at any given incidence during a ramp-down test, the wake was significantly larger than in an equivalent static test. This observation was in addition to the delay in progress of attachment along the chord.

It is suggested that an excess of wake fluid builds up during ramp-down motion due to the sluggish convection of this fluid away from the aerofoil. As the flow becomes attached around the leading edge of the aerofoil, the fluid ahead of the wake partially stagnates as it approaches it, and accelerates around it. The pressure gradient observed in the experimental data reflects the above proposed description. The formation of the pressure gradient pushes excess wake fluid off the aerofoil surface, leaving a thinner wake behind the separated shear layer.

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Figure 1 Flow visualisation of ramp-down test. The flow direction is from right to left. The incidence is 4° . The excess wake fluid is above the white dashed line.

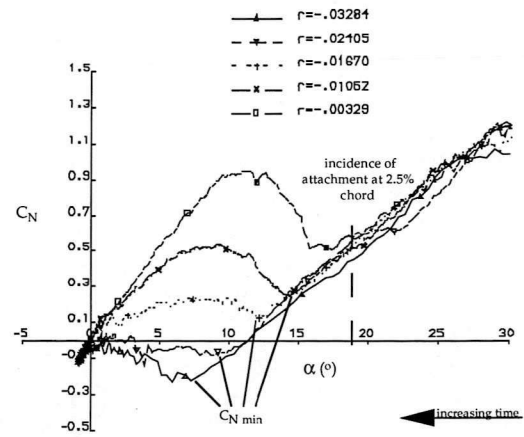


Figure 2 The variation of normal force with incidence during a ramp-down test. The effect of pitch rate is shown.

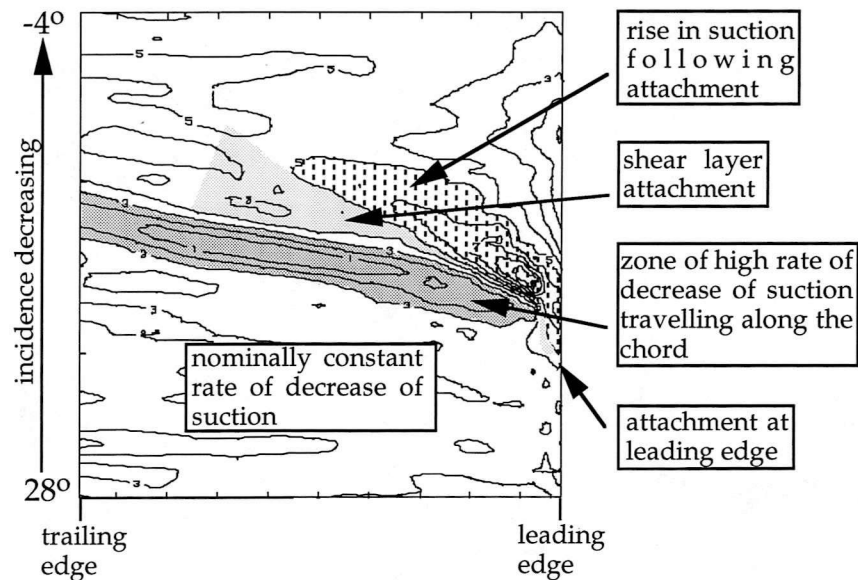


Figure 3 Contour plot of rate of change of suction along the aerofoil chord during a ramp-down test. Contours 1-3 are decreasing suction, 5-9 are increasing suction.

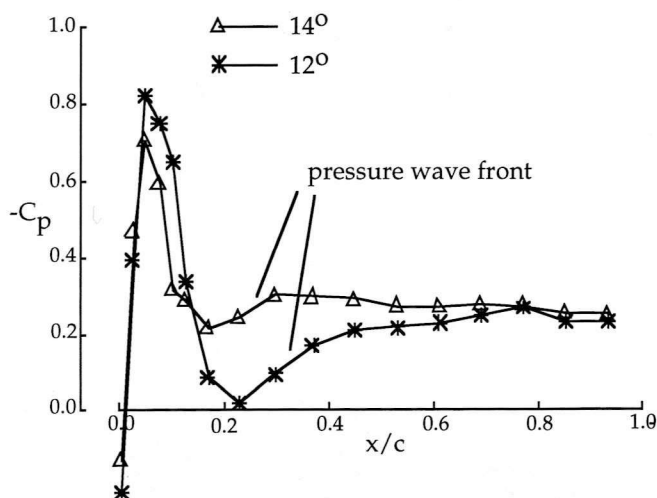


Figure 4 Chordwise pressure distributions over the lee surface of the NACA 23012B showing the development of the ramp-down pressure wave.

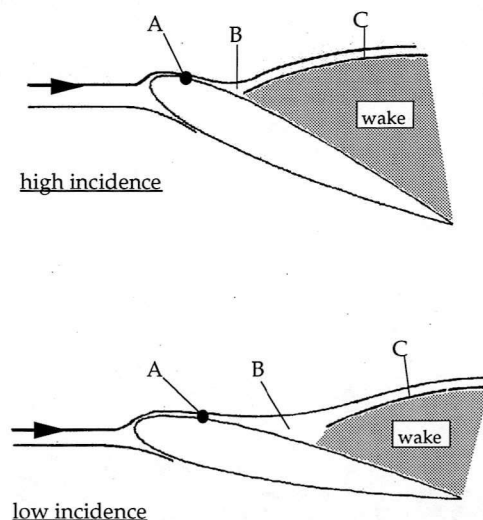


Figure 5 Schematic of the flow during a ramp-down test showing the wake fluid and wake boundary. A is the attachment, B is the thinned wake and C is the wake boundary.